TOPIC- LASER INDUCED FUSION

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INTRODUCTION -

The goal of the fusion research is to derive energy from the fusion of light atomic nuclei. Nuclear Fusion is a reaction where two or more loosely bound ligh nuclei combine to form a heavier tightly bound nucleus. As we know that the fusion is the energy source of the sun and stars.Reactors based on laser induced fusion is one of the method designed by the scientists to achieve fusion in a controlled manner.Before discussing about the fusion process,let us first briefly understand the components of the nucleus and nuclear forces.A Nucleus of an atom consists of proton and neutron generally called ‘nucleon’.As proton being positively charged and neutron being neutral,no coloumbic force exist between them.Since nucleons are held together in the nulceus ,there is a short range attractive force called nuclear force .The minimum energy required to break the nucleus into its constituent nucleons is called binding energy.

Consider the nuclear reaction :-

Deuterium + Deuterium → Tritium + Hydrogen

where B.E(deuterium)=2.2 eV ; B.E(tritium) =8.08 eV
Thus the gain in binding energy = 8.08-(2×2.02)= 4.04 eV.
This means a loosely bound system goes over to a tightly bound system resulting in the liberation of energy; this energy appears in the form of kinetic energies of tritium and proton,

Consider another nuclear reaction :-

Deuterium + Tritium → alpha particles (3.5 MeV) + neutron(14.3 MeV)

where the total energy liberated is 17.6 MeV
D-T reaction is 100 times more probable than D-D reaction.

Why do we need laser for fusion process?

For fusion reaction to occur,nucleui should have high kinetic energy to overcome Coulombic repulsion between the protons.Thus the temperature required for this is of the order of 10^7 Kelvin and at such temperature matter is in ionised state called plasma state.

Two major problems in thermonuclear fusion are :-
a) heating of plasma to such a high temperature.
b) confinement of plasma for fusion reactions to occur.

Confinement time in nuclear fusion devices is defined as the time within which the plasma is maintained at a temperature above the critical temperature required for ignition.It is given by a criterion known as "Lawson criterion" i.e $n\tau \geq 10^{14}$ cm^{-3} s ,where n is the plasma density and τ is the confinement time.
For the confinement of plasma ,magnetic field is used .The magnetic confinement approach is based on the interaction of charged particles with magnetic fields.We know that the charged particles are deflected by a magnetic field and, if the field is strong enough, particles will move around the magnetic field lines, gradually progressing along it if they have some longitudinal velocity components.Tokamak was designed by the Russian scientist Basov, and since then it has become the leading magnetic confinement concept. Tokamak stands for "Toroidal magnetic chamber".
Problems with magnetic confinement:-
a) Requirement of High magnetic fields (5-10 T)
b) However Tokamak has come close to satisfy Lawson Criterion but still confinement of the plasma is a big issue.

With the development of laser,new ideas of fusion has emerged.When laser pulse interacts with the D-T pellet,inertial forces are generated which helps in compressing,heating and confining of the material.Instead of magnetic fields, the plasma is confined by the inertia—hence the this type of fusion is also called 'Inertial Confinement Fusion'.

For Laser fusion,we check 'ρR' criterion instead of 'Lawson Criterion' where ρ is the density of fuel and R is the radius of the fuel .

How ICF works?

We take a pellet which contains solid D+T and there we bombard the pellet with laser beams.Due to the bombardment of the beam, ablation of the D-T from outer surface starts taking place (or say ionization started).As there is a tranfer of the energy from the beam to the pellet,the Corona part is hotter than the Core part of the pellet due to which there is a temperature gradient .Since pV=nKT(ideal gas equation),there is a pressure gradient also.
Shockwaves are generated when there is steep change in pressure over a short duration of time.In ICF, pressure is applied during ablation . This ablation pressure is related to the laser intensity.Laser Pulse durations are a few nanoseconds ,so there is a steep rise in intensity, a flat region on the top of order of a few nanoseconds, followed by a sharp drop in intensity thus creating Shockwaves.These Shockwaves flow towards the core resulting in transfer of heat to the core and compression of the

core and the fusion energy is released from high compression densities along with the high temperature.

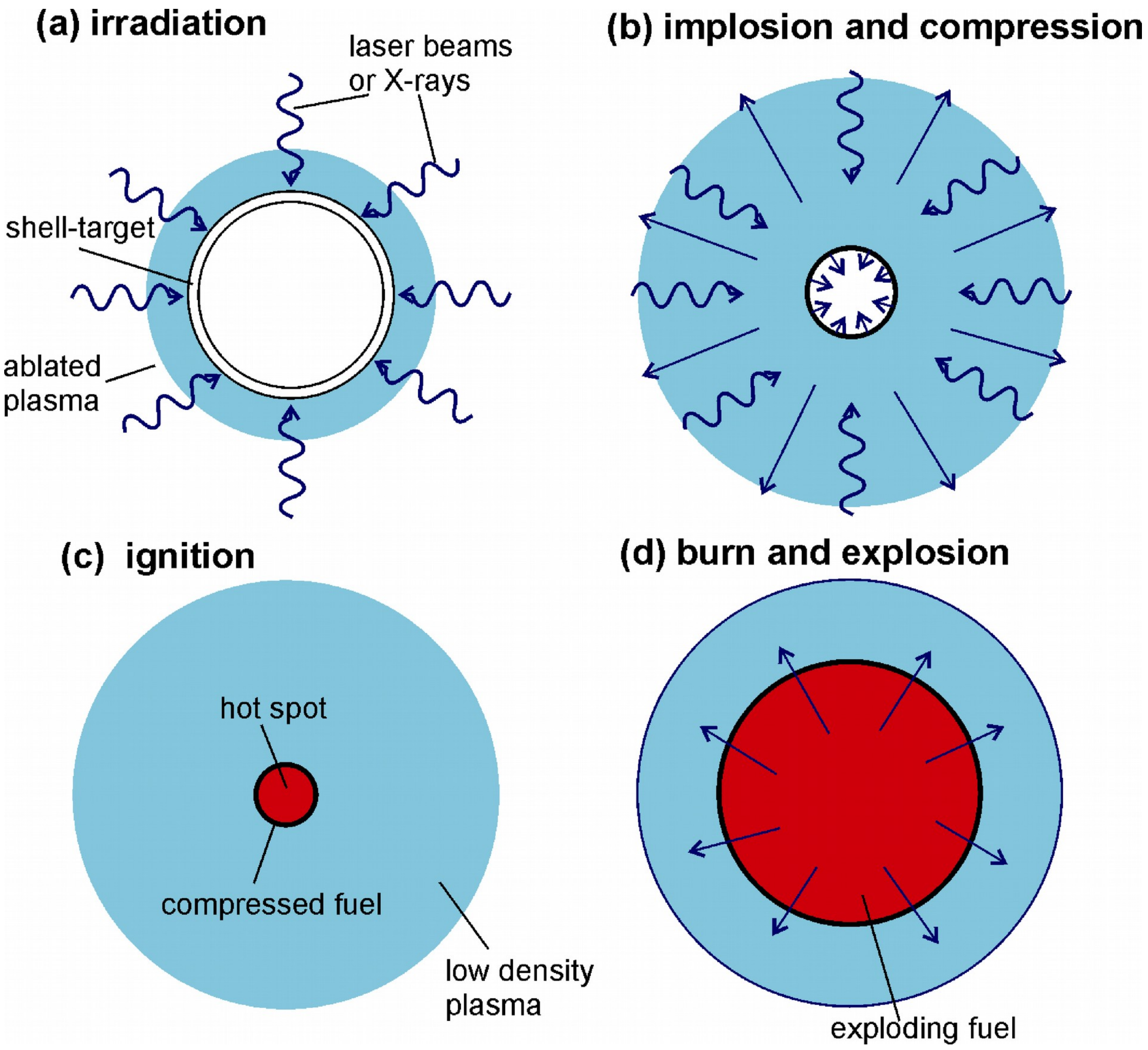

Fig:- stages of laser fusion

Advantages of Laser fusion -

For fusion reaction to occur energy required is of the order of MJ .We can get this much amount energy by using an electron beam also then why do we need intense laser pulse?

Here are the few problems --

a) There are chances that electron beam can interact with the material ,so vacuum is needed for Electron beam systems to operate, while lasers can operate in air.

b) To achieve ignition in inertial confinement fusion the driver beam must deliver about 1MJ of energy to a target size of about a millimeter in less than 10ns time

interval (by Lawson criterion). This corresponds to power of more than 100TW. For an electron beam there will be the space charge due to which beam will not be focussed.
For example, assuming electron energy E=50keV (v≈0.44c), total charge would be Q=e·1MJ/E≈−20C. Twenty Coulombs is an *enormous* charge, and for a 10ns time interval it must be spread along the bunch of about (10ns×0.44c) ≈ 1.3m length. Thus it would be impossible to focus such a beam.
However the heavier ions have lower charge to mass ratios,so the space charge ratio will be significantly less and thus heavy ion fusion (HIF) is a new scope for a viable fusion power technology.

Advanced Concept to Laser Fusion --

Plasma is created when laser hits the D-T target.The momentum of the plasma is balanced by the momentum of the inner part of target leading to implosion and compression of fuel.So there will be a decrese in volume with which temperature and fuel density will increase.With sufficient reduction in volume,the temperature in the centre rises very high.A "hot spot" is formed which will allow self-ignition of the fuel referred as " Central hot spot ignition" (CHSI). To have the energy produced in the fusion reaction higher than the energy of the laser,density of the compressed fuel should be high and such high densities of the DT fuel using CHSI method requires the nanosecond laser(~10ns) with high energy,high symmetry of the target and sevral other requirements.

In the year 2014,US National Ignition Facility achieved the first laser-driven fusion for releasing more energy through nuclear reaction than absorbed by fuel to start with.But the goal of creating self-sustaining reaction that produces more energy than it consumes was still a long way off.However some new concepts have been developed in this field such as -

a) Fast Ignition :- Fast Ignition is a method which differs from the conventional one in such a way that there are seperate drivers for compression and ignition of Hydrogen fuel.The fuel is pre compressed by a long pulse(ns) driver and then ignited by a short pulse(ps) intense laser.Fast ignition has an advantage of : higher gain,lower overall driver energy,reduction in symmetry requirements, and flexibility in compression drivers.

b) Shock Ignition :- Shock Ignition is another new concept in this field proposed by Betti et al..In this approach the 'ignitor' is a strong converging shock waves generated by the D-T target in the final stage of compression with the most intense final part of appropriately shaped laser pulse compressing the fuel.The fuel is first irradiated symmetrically at lower velocity than conventional hot spot ignition.The temperature of hot spot generated at the end of implosion is below the ignition threshold. Towards

the end of implosion,the fuel pellet is irradiated by a nano second pulse which drives a strong converging shock wave which is amplified by colliding with the outgoing shock waves from the centre.The hot spot then undergoes additonal heating and gets ignited.
The main advantages of this method are :
a) relatively low laser power (200–300 TW) and energy (200–300 kJ) needed for ignition
b) high energy gain

c) Impact Ignition :-In this approach,rapid heating of the compressed fuel is the result of impact of a microprojectile of mass m~ 10^{-6}-10^{-4} g accelerated to the velocity of >1000 km/s.A microprojectile made of material 'Au' and accelerated at 5×10^{6} m/s^{-2} collides with the compressed D-T fuel.After collision,a large fraction of micro-projectle energy is transferred to fuel in a very short time (~10^{-11}s)).As a result of this,a hot spot is created which will ignite the fuel.Here ,the maximum kinetic energy of the projectile is only of the order of few kJ which is much lower than the laser energy needed to compress a fuel.
Advantages of this method is :
a)Much lower driver energy.
b) High Energy gain.

References -

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